Monitoring cure and detecting damage in composites with embedded sensors.

James S Chilles[1], **Anastasia F Koutsomitopoulou**[1],**Anthony J Croxford**[2], **Ian P Bond**[1]

[1] Advanced Composites Centre for Innovation and Science, University of Bristol, Queen's Building, Bristol BS8 1TR, UK

[2] Department of Mechanical Engineering, University of Bristol, Queen's Building, Bristol, BS8 1UB, UK

E-mail: `jc9191@bristol.ac.uk`

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Abstract.
This paper demonstrates the capability of embedded piezoelectric sensors to monitor the state of health throughout the lifetime of composite structures. Sensors were embedded into fibre reinforced composites and used to monitor the progress of cure during manufacture, and the subsequent damage state of the cured part. The sensors used in this work consist of a single piezoelectric transducer, which is electronically connected to an inductance coil. A probe containing two inductance coils was used to make wireless ultrasonic measurements. When the probe was placed in close proximity to an embedded sensor, the electromagnetic coupling between the coils in probe and the embedded coil, allowed electronic signals to be wirelessly transferred between the transducer and the ultrasonic processing equipment. Two different inductively coupled transducer systems (ICTS) were used to monitor cure. A ICTS which generated bulk waves monitored the cure of a thick glass fibre section, and an ICTS which generated guided elastic waves monitored the cure of a large glass fibre plate. To characterise the cure monitoring ability of each ICTS, two established cure monitoring techniques; differential scanning calorimetry (DSC) and dielectric analysis, were used to record measurements during cure. The guided wave ICTS was then used to detect barely visible impact damage (BVID), created by a 10 Joule impact at a distance of 300 mm from the sensor embedded in the large glass fibre plate.

1. Introduction

The susceptibility of composite materials to impact damage at relatively low energies (10-30 Joules) [1, 2] makes the use of health monitoring networks appealing for structural composite parts. Sensors can be either surface bonded, or embedded within a composite part and used to detect damage throughout the components lifetime. Embedding sensors inside the host structure is an attractive option, as each sensor is afforded physical protection from its operational environment, potentially improving the durability of the health monitoring network. Embedding sensors into the stacking sequence of composite parts during manufacture rather than surface bonding the sensors to the structure post manufacture, brings the additional benefit of allowing each sensor to monitor the curing process of the surrounding material. The embedding of sensors inside composite materials remains an open research topic [3, 4, 5], however it has been shown that with careful consideration of the laminates stacking sequence and the technique used to embed the sensors, sensors can be embedded without significantly reducing the strength of composite materials [6].

In this study ultrasonic sensors were embedded into the stacking sequence of glass fibres pre-impregnated with epoxy resin (prepreg), and used to monitor the progress of cure in autoclave type manufacturing processes. Autoclave processes are the most widely used manufacturing route for structural aerospace components [7, 8], and although capable of producing high quality parts, with low voidage and a high fibre volume fraction, they incur high costs [9, 10]. The high cost and complexity associated with autoclave processes (and many other methods of composite manufacture), have created demand for techniques capable of providing real time data during cure, to ensure that parts are fully cured in the minimum amount of time. Numerous cure monitoring methods exist of which measurements of the dielectric permittivity [11, 12, 13, 14], and ultrasonic techniques [12, 15, 16] are two of the most prominent macroscopic scale approaches, whilst differential scanning calorimetry (DSC), can be used to analyse the behaviour during cure of small laboratory samples (measuring tens of milligrams) [15, 17, 18]. All of these techniques can provide detailed analysis of the curing process, but each requires specialist equipment which can be of considerable expense; ultrasonic techniques often require transducers to be embedded into the tooling [19, 20], whilst measurements of the dielectric permittivity are typically recorded by embedded sensors which become redundant post manufacture [14, 21]. The ultrasonic sensors investigated in this study are capable of monitoring the curing process during manufacture, and the damage state of the structure post manufacture. The ability to monitor the state of health for the full life cycle of a part, is an advantage when compared with the previously mentioned cure monitoring techniques, which provide no damage monitoring capability, and would require additional systems to detect damage during operation of the structure.

The second section of this paper, uses an embedded sensor previously used to monitor the curing process, to detect low energy impact damage in a cured part. The susceptibility of composite materials to low energy impact damage is problematic in safety critical aerospace structures. Low energy impacts which can be caused by bird strikes, tool drops or poor handling of the parts may result in damage forming beneath the impacted surface, termed barely visible impact damage (BVID) [1, 2]. BVID is extremely difficult to detect by visual inspection, and can result in catastrophic failure of the structure. The aerospace industry has adopted a strategy of limiting the strain of composite parts (to prevent the propagation of BVID) [22], and applying rigorous inspection programmes using ultrasonic C-Scan and X-Ray imaging techniques, both of which require parts to be taken out of service for inspection [23]. Although this approach results in safe aerospace structures, it creates expensive inspection programmes, and typically, composite parts that are over engineered. Networks of sensors that are either embedded or permanently attached to composite structures, could increase the automation of inspection; reducing the time and cost of inspection programmes, whilst potentially increasing the sensitivity to impact damage, and allowing aerospace engineers to design composite parts to operate at higher strains, producing lighter more efficient composite structures.

The sensors investigated in this study use piezoelectric disks to generate ultrasonic waves, and evaluate the condition of the host structure through the reflected waveforms. Similarly the SMART layer [24, 25] developed at Stanford University, uses ultrasonic waves generated by piezoelectric disks to monitor the state of health. The layer consists of a number of piezoelectric transducers which are bonded to a continuous sheet of printed circuit board. The layer can be embedded within composite laminates as an additional ply, and used to identify damage by making pitch catch ultrasonic measurements between each piezoelectric actuator and sensor pair. In addition to providing damage detection capability, the layer can be used to monitor the progress of cure [24].Optical fibre sensors are another example of a sensing technique capable of detecting damage and monitoring the curing process of composite materials [26, 27]. The fibres are of minimal diameter (40-250 μm) [28], allowing them to be embedded within composite materials and used to monitor both the temperature and strain applied to a structure, by measuring variations in the local strain field [29]. Fibre optic sensors have been shown to be capable of detecting delaminations, but require complex and typically heavy equipment to interrogate them, and unless used in combination with piezoelectric transducers (used to generate ultrasonic waves)[30, 31, 32], an extremely high density network of optical fibres would be required to detect impact damage in a large composite structure. Alternative systems based on measuring variations in the electrical resistance between embedded electrodes, have displayed the capability to detect impact damage in composites reinforced with conductive carbon fibres [33, 34]. An example of such a system is that developed by Swait et al. [35], in which arrays of embedded electrodes (with a 10 mm lateral spacing) etched from printed circuit board were used to identify the presence of impact damage events between electrode pairs separated by a distance of 1 meter. The relatively small lateral spacing of the electrodes would require a high number to be embedded in a large composite structure, and an extensive network of wired connections. Whilst all of the previously mentioned systems show promise as health monitoring networks, their implementation on a large composite structure, is limited by the requirement to have an extensive network of wired connections and complex control units, which not only add weight to the structure, but potentially decrease reliability due to wiring failures, and possibly compromise the host structures strength due to failure initiation at the wiring, as was observed in the work of Tang et al [36].

This study monitors the progress of cure and damage state (post manufacture) of composite parts, using a unique wireless embedded sensor. The sensors are separate units which can be operated independently. Each sensor contains a single piezoelectric transducer, which generates and receives ultrasonic waves that are used to evaluate the condition of the host. The transducers are connected to an inductance coil, which enables electrical signals to be wirelessly transferred to an external probe via inductive coupling (covered in more detail in Section 2). Sensors were embedded into a thick monolithic section and a large plate, both made from glass fibre reinforced prepreg material. The parts were cured in autoclave type manufacturing processes. In each case a single sensor was embedded, and used to record pulse echo measurements for the duration of each curing process. To evaluate the sensitivity of the embedded sensors to cure, the performance was compared to that of two conventional cure monitoring techniques; differential scanning calorimetry (DSC) and dielectric analysis. The sensor embedded in the large plate was then used to detect the presence of BVID caused by a 10 Joule impact post manufacture.

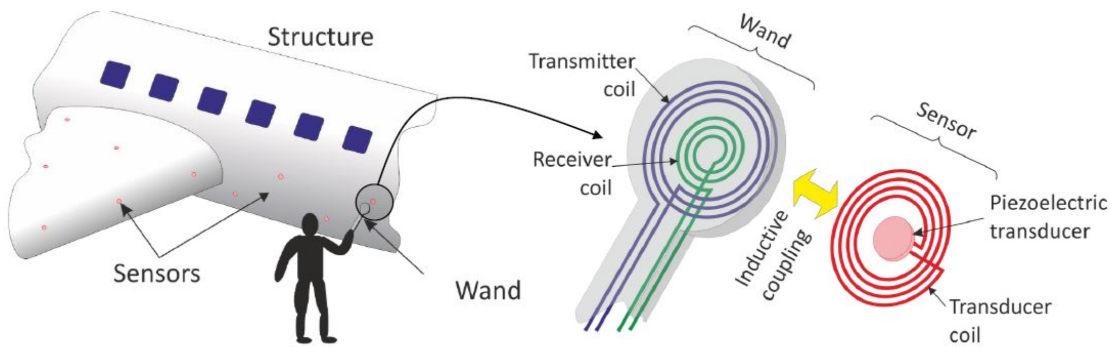

Figure 1. Manual inspection of an aeroplane using the inspection wand, and diagram illustrating the inductive coupling between the three coil network.

2. Inductive Coupling

Inductive coupling is used to transfer electrical signals between the embedded sensors and the ultrasonic processing equipment, allowing sensors to be embedded without the need for the ingress of connecting wires. The electromagnetic coupling is achieved using a three coil network. One coil (termed the transducer coil) is connected to the embedded piezoelectric transducer. The other two coils (termed the transmitting and receiving coils) are contained within an inspection wand, and are connected to the outputs and inputs of the ultrasonic instrumentation. When the inductance wand is held in close proximity to the embedded sensor, electrical signals are transferred between the three coils, enabling ultrasonic measurements to be made using the embedded piezoelectric transducer (as shown in Figure 1). The electromagnetic coupling was optimised, by identifying the suitable geometrical properties for each of the coils using a model published by Zhong et al. [37].

The system allows for rapid contactless measurements to be made, with a separation distance between sensor and inspection wand in the order of tens of millimetres [38]. The advantages that this system holds over conventional NDT measurements made using external transducers, are the speed and ease at which measurements can be made, and the possibility of employing baseline subtraction techniques, due to measurements being taken from fixed locations within a structure. Baseline techniques allow the signal caused by a damage event to be more easily identified in complex geometries, even in the presence of thermal variations [39]. Whilst the system does not represent a fully integrated structural health monitoring system; requiring either manual inspection, or the use of an automated vehicle. The removal of data processing, or long range wireless data transmission requirements, allows the size and weight of the sensors to be reduced, which is beneficial in reducing the on structure weight, as well as allowing the sensors to be embedded without significantly reducing the mechanical properties of the composite part.[6] The implementation of baseline subtraction techniques to detect damage, and signal processing techniques used to account for misalignment between the embedded sensor and wand are covered in detail in the work of Zhong et al.[38]

3. Cure Monitoring

In this section inductively coupled sensors were embedded into the stacking sequence of glass fibre prepreg, and used to monitor the progress of cure. Two specimens were manufactured. A thick glass fibre section (Figure 2a), and a large glass fibre plate (Figure 2b). Two different types of inductively coupled transducer systems (ICTS) were used to monitor cure. An ICTS which generated bulk waves, that propagated through-thickness, monitored the cure of the glass fibre block shown in Figure 2a. An ICTS which generated guided elastic waves, that propagated in the plane of the fibres, providing large area coverage, monitored the cure of the glass fibre plate shown in Figure 2b.

3.1. Manufacture

3.1.1. Bulk wave specimen

The composite specimen shown in Figure 2a was manufactured from a unidirectional glass fibre epoxy prepreg material (Cytec, Cycom 950-1 glass fibre reinforced). The laminate was made from a total of forty plies, and with the layup shown in Figure 2a, producing a laminate with a total cured thickness of 10.4 mm. Individual plies were laid down by hand onto an aluminium tool plate. A single inductively coupled bulk wave sensor of diameter 35 mm and a maximum thickness of 1 mm, was placed on top of the outer most ply. The assembled stacking sequence was then sealed within a vacuum bag, and cured inside an autoclave under 7 bar of pressure. The cure cycle contained a 95 minute dwell period at 95°C, to prevent excessive exothermic reactions occurring during cure. The temperature was then increased and the composite cured at 125°C for 155 minutes, as advised by the manufacturer.

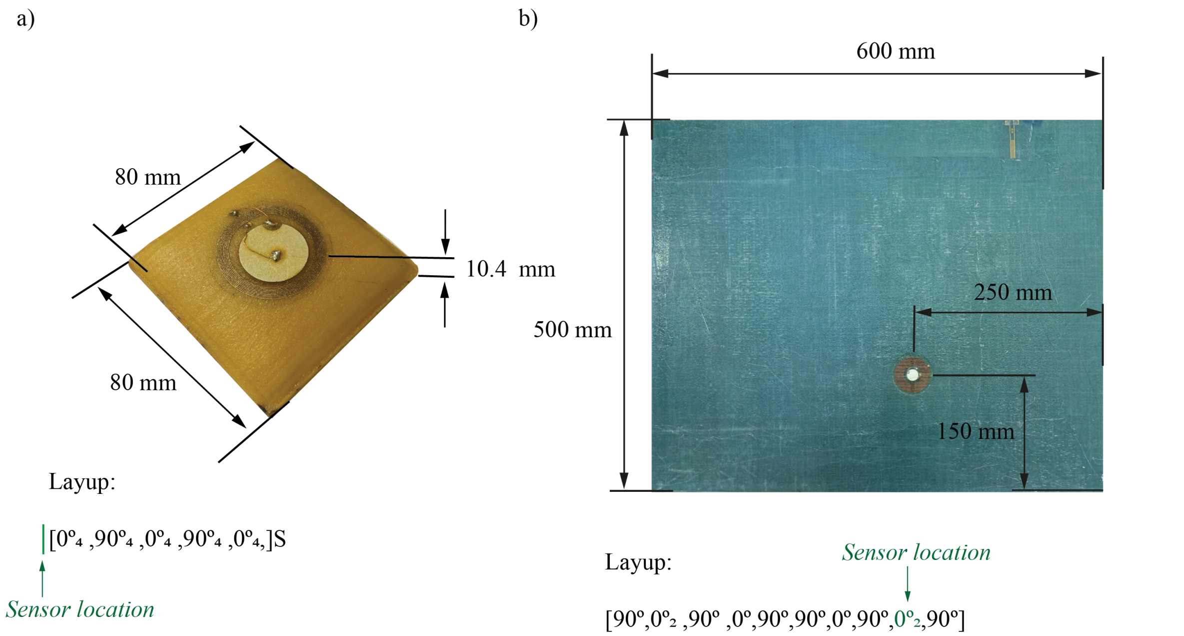

Figure 2. a) Thick composite section, containing an embedded bulk wave sensor. b) Large glass fibre epoxy plate, containing a guided wave sensor, and an embedded comb electrode (top right hand corner of the plate).

3.1.2. Guided wave specimen

The large thin plate shown in Figure 2b was manufactured from a unidirectional glass fibre epoxy prepreg material (Gurit, SE70 glass fibre reinforced). The stacking sequence shown in Figure 2b was assembled by laying down sheets of prepreg onto an aluminium tool plate. The total thickness of the laminate was 3.31 mm. A region of prepreg 50 mm in diameter was cut from the plies labelled as sensor location in Figure 2b, and a single guided wave sensor of diameter 50 mm and maximum thickness of 0.3 mm was embedded into the cut out region (Note that it is not required for the plies to be cut to embed the inductively coupled sensors, but it was selected as the embedding method in this case). The plate and sensor, were sealed within a vacuum bag, and cured inside an oven at 110°C for 75 minutes, under a pressure of 1 bar (applied by a vacuum pump) as advised by the manufacturer.

Table 1. Details of the piezoelectric transducers contained within each sensor type.

Sensor	Material	Diameter (mm)	Thickness (mm)	Centre Frequency (MHz)	Deformation mode
Bulk Wave	PZT - NCE51	20	1	2	Through-thickness
Guided Wave	PZT - NCE51	16	0.3	0.165	Radial

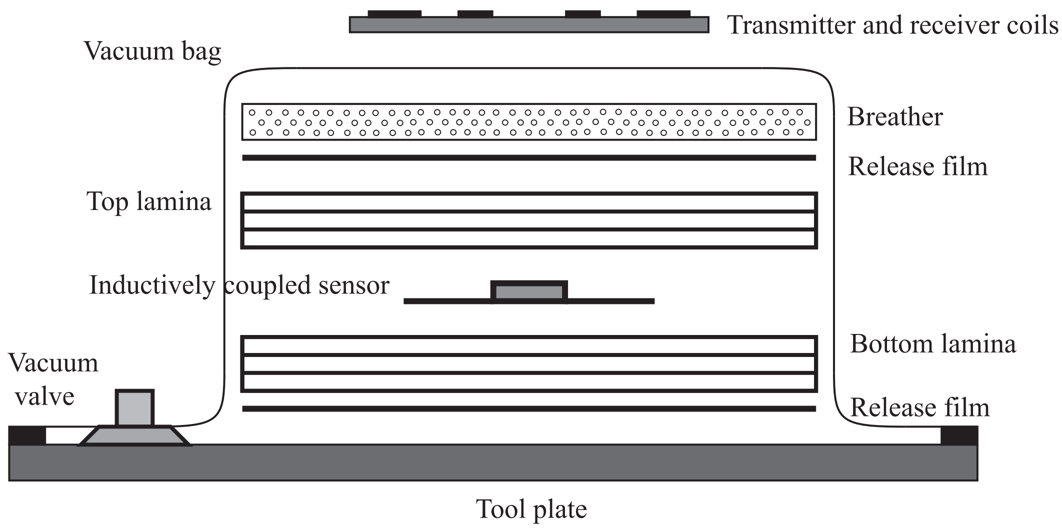

Figure 3. Setup used to record ultrasonic measurements throughout the curing process.

3.2. Methodology

3.2.1. Monitoring cure with ICTS

The experimental setup used to record ultrasonic measurements is shown in Figure 3. The transmitter and receiver coils were placed onto the vacuum bag directly above the embedded sensor, allowing the electromagnetic coupling to wirelessly transfer electrical signals between the three coils, and enabling ultrasonic measurements to be recorded without altering the vacuum bag. A combined digital-oscilloscope signal-generator unit (HS3, TiePie Engineering) was used to generate an excitation signal with a peak-peak voltage equal to 24 Volts. An input signal of a 5 cycle hanning windowed tone burst was transmitted to the embedded sensors. The centre frequency of each input signal is shown in Table 1. In each case a single sensor was embedded into a composite part and used to record pulse echo measurements every 30 seconds, for the duration of the curing process.

The bulk wave sensor (2 MHz operating frequency, Table 1) embedded into the thick composite part (Figure 2a) propagated bulk ultrasonic waves through-thickness, providing localised coverage. The progress of cure was followed by monitoring the reflection received from the back wall of the thick glass fibre laminate. This method of cure monitoring is similar to conventional ultrasonic cure monitoring methods, in which external transducers are used to make bulk wave measurements across the thickness of a curing part [12, 15, 19, 20].

The cure of a large glass fibre plate (Figure 2b) was monitored using an embedded guided wave sensor (165 KHz operating frequency, Table 1). Guided waves are characterised by their ability to propagate over large distances, and are therefore an attractive option for long range detection. However, guided waves are dispersive with multiple wave modes existing at any given frequency. To reduce these effects, the guided wave ICTS operated at a relatively low frequency-thickness product of 0.53 MHz.mm, which resulted in the waves generated by the embedded transducer being dominated by a non-dispersive region of the fundamental symmetric wave mode (So). The attenuation of the So mode due to material damping is significantly less than that of the fundamental flexural mode (Ao) [40], which also exists at this frequency thickness product. The axisymmetric radial mode of the guided wave sensors transducer (Table 1), provided increased sensitivity to the So waves, which are dominated by in-plane motion. The guided wave ICTS measured cure progress, by monitoring the reflections received from the edges located at distances of 150 mm and 250 mm from the embedded inductively coupled sensor (Figure 2b).

3.2.2. Monitoring cure with DSC and dielectric analysis

A TA Q200 DSC, was used to study the cure of both the glass fibre materials cured during this work (Gurits SE70, and Cytec Cycom 950-1). Samples of uncured prepreg weighing approximately 10 mg, were placed into Tzero aluminium hermetic pans, and cured using the same curing profile as was used to cure the glass fibre parts containing inductively coupled sensors. The degree of conversion was measured at various stages of the curing process, using the equation.

$$\alpha = \frac{H_T - \Delta H_R}{H_T}, \tag{1}$$

Where α is the degree of conversion, H_R the total enthalpy of reaction, and ΔH_T the residual enthalpy of reaction. The enthalpies of reaction were measured using a heating rate of 10°C min^{-1}, across a temperature range of 0°C - 250 °C, and with a nitrogen purge gass flow rate of 50 ml min^{-1}

Dielectric measurements were performed using a dielectric monitoring system (DETA-SCOPE^{TM}, ADVISE E.E., Greece). A sinusoidal voltage of 10 Volts, and a frequency scan over a range of 1Hz to 0.1MHz was used in each measurement. In this study, commercially available sensors (GIA) comprising an assembly of interdigitated electrodes printed on a polymeric film were used. The sensors were embedded into the stacking sequence of each prepreg material (Gurit SE70, and Cytec Cycom 950-1) prior to vacuum bagging.

3.3. Results

3.3.1. Bulk wave ICTS results

An example of the pulse echo data captured during the cure of the 10.4 mm thick glass fibre laminate (Figure 2a) by the bulk wave ICTS is shown in Figure 4. The ultrasonic data was normalised by the amplitude of the back wall reflection at the end of the curing process. The degree of conversion measured by DSC is plotted in Figure 5a. The degree of conversion measurements show that the majority of the cure reaction had

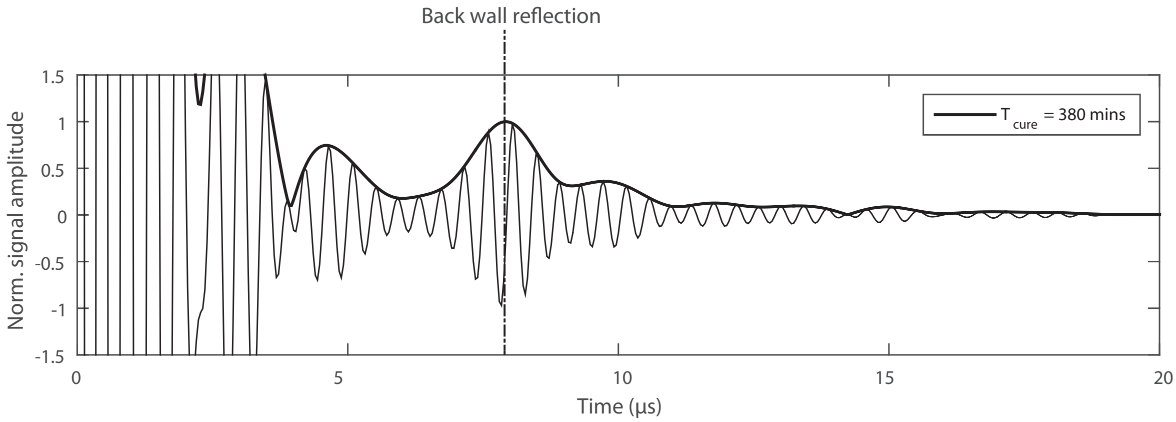

Figure 4. Pulse echo data recorded by the bulk wave ICTS at the end of the curing process (time of cure equal to 380 minutes).

taken place by 250 minutes. After 260 minutes no change was seen in the degree of conversion data, indicating the end of cure. The evolution of the Imaginary Impedance Maximum (IIM); which corresponds to the maximum value of imaginary impedance recorded in a frequency sweep [41, 42], is plotted in Figure 5a. Prior to wetting of the sensor with resin (before 50 minutes, Figure 5a) the magnitude of the IIM was 10^9-10^{10} Ohm, which corresponds to the response of the sensor in air. Upon heating the resin, a large drop in the impedance was observed, which indicated that a finite electric current was established, due to migration of the charged species within the resin. The increased temperate of the epoxy resin, reduced the viscosity of the resin and thereby facilitated molecular mobility, which led to a reduction in the IIM (between 50 and 230 minutes, Figure 5a). After this decrease, the IIM increased due to the chemical reaction taking place. The formation of the three dimensional polymeric network increased the viscosity of the mixture, and hence the IIM. At 260 minutes, the IIM reached a constant value indicating cure completion [41].

Both the amplitude and velocity of sound associated with the back wall reflection (labelled in Figure 4) are plotted against curing time in Figures 5b and 5c. The bulk wave sensor could not identify the back wall reflection until 250 minutes into the curing process. Prior to this point a combination of the waves being scattered at the boundaries between unbonded plies, and the reduced viscosity of the resin, led to the propagating ultrasonic waves being heavily attenuated. After 250 minutes, sufficient cure had taken place to allow the back wall reflection to be identified. Between 250 and 280 minutes there was a rapid increase in both the amplitude and velocity of sound, indicating that there was a large increase in the elastic modulus of the curing epoxy resin. No change was seen in the velocity data after 300 minutes. The measurements of amplitude showed a high sensitivity to the final stages of cure, with the amplitude data converging to a constant value at 380 minutes.

The results show that in the case of an embedded transducer generating bulk ultrasonic

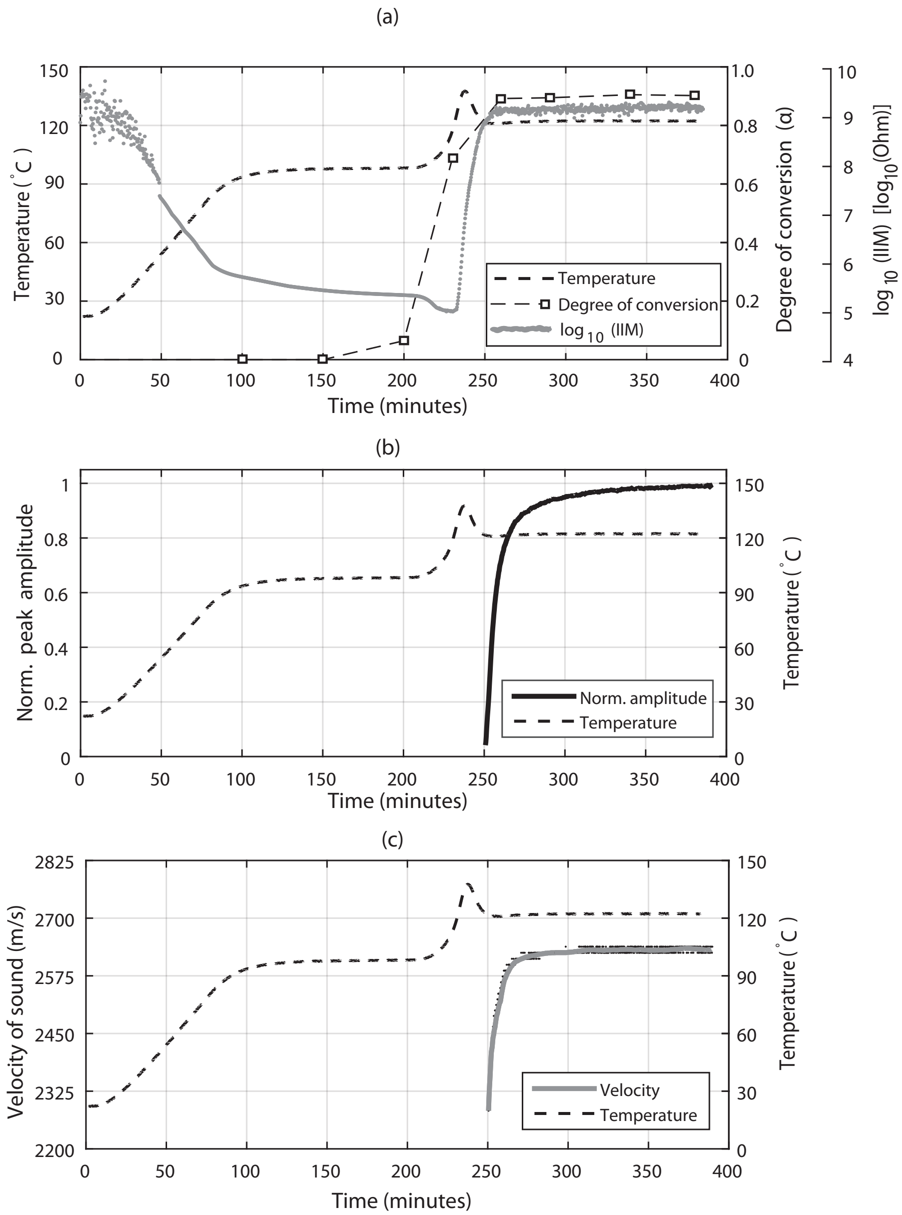

Figure 5. Data obtained from the cure of the 10.4 mm thick glass fibre section shown in Figure 2a. a) Degree of conversion measured by DSC, and the time evolution of the imaginary impedance maximum (IIM) recorded by dielectric analysis. b) Normalised amplitude of the received back wall signal. c) Velocity of sound.

waves, measurements of amplitude show a higher sensitivity to the final stages of the curing process than measurements of velocity. The bulk wave measurements recorded by the ICTS are in agreement with those made using external transducers; the attenuation experienced by the ultrasonic waves decreased, and the velocity of sound increased as the part cured [12, 15, 19, 20]. The bulk wave ICTS displayed a high sensitivity to the final stages of the curing process, with the ultrasonic amplitude data plateauing later than the degree of conversion, and IIM measurements. However, the ICTS was not able to record any data before 250 minutes into the curing process.

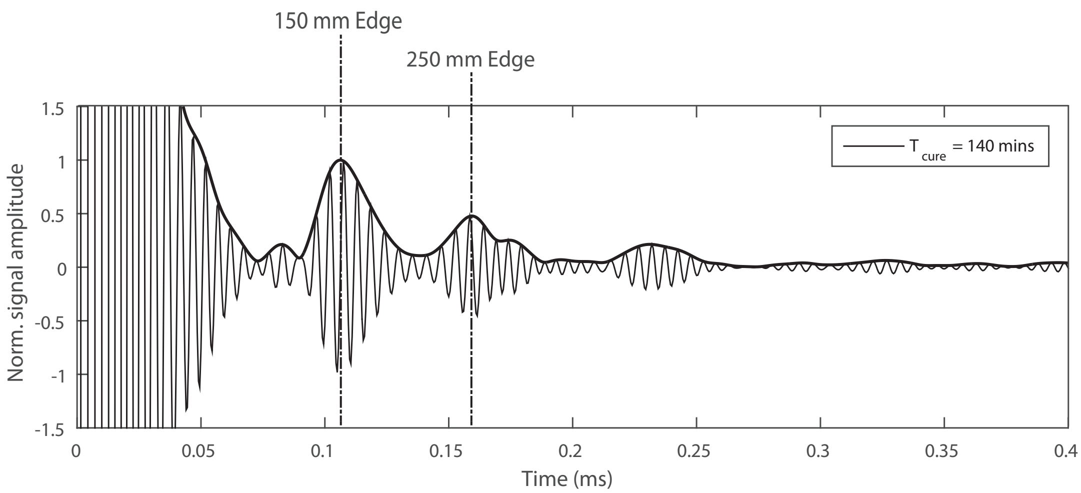

Figure 6. Pulse echo data recorded by the guided wave ICTS at the end of the curing process (time of cure equal to 140 minutes).

3.3.2. Guided wave results

Figure 6 is an example of the pulse echo data recorded by the guided wave ICTS during the cure of the large glass fibre plate shown in Figure 2b. The ultrasonic data has been normalised by the amplitude of the closest edge reflection at the end of the curing process (located 150 mm from the sensor, Figure 2b). The peaks which correspond to the arrivals of the So wave mode from the two closest edges are labelled in Figure 6. The degree of conversion measured by DSC is plotted in Figure 7a. The data shows that the majority of the cure reaction had taken place by 60 minutes. The degree of conversion reached a steady value at 75 minutes, indicating the end of cure. The evolution of the Imaginary Impedance Maximum (IIM) is plotted in Figure 7a. Prior to wetting of the sensor with resin (before 26 minutes, Figure 7a) the magnitude of the IIM was 10^9-10^{11} Ohm, which corresponds to the response of the sensor in air. Upon heating the resin, a large drop of the impedance was observed. Which indicated that a finite electric current was established, due to migration of the charged species within the resin. The IIM decreased further as the cure cycle progressed due to temperate of the epoxy resin increasing, which reduced the viscosity and thereby facilitated molecular mobility (between 26 and 40 minutes, Figure 7a). After this decrease, the IIM increased due to the chemical reaction taking place. The formation of the three dimensional polymeric network increased the viscosity of the mixture, and hence the IIM. At 85 minutes, the IIM reached a constant value indicating cure completion [41].

Measurements of the normalised peak amplitude, and velocity of the So wave mode are shown in Figures 7b and 7c. Unlike the bulk wave measurements, the guided wave ICTS was capable of recording data at the start of the curing process, with the embedded

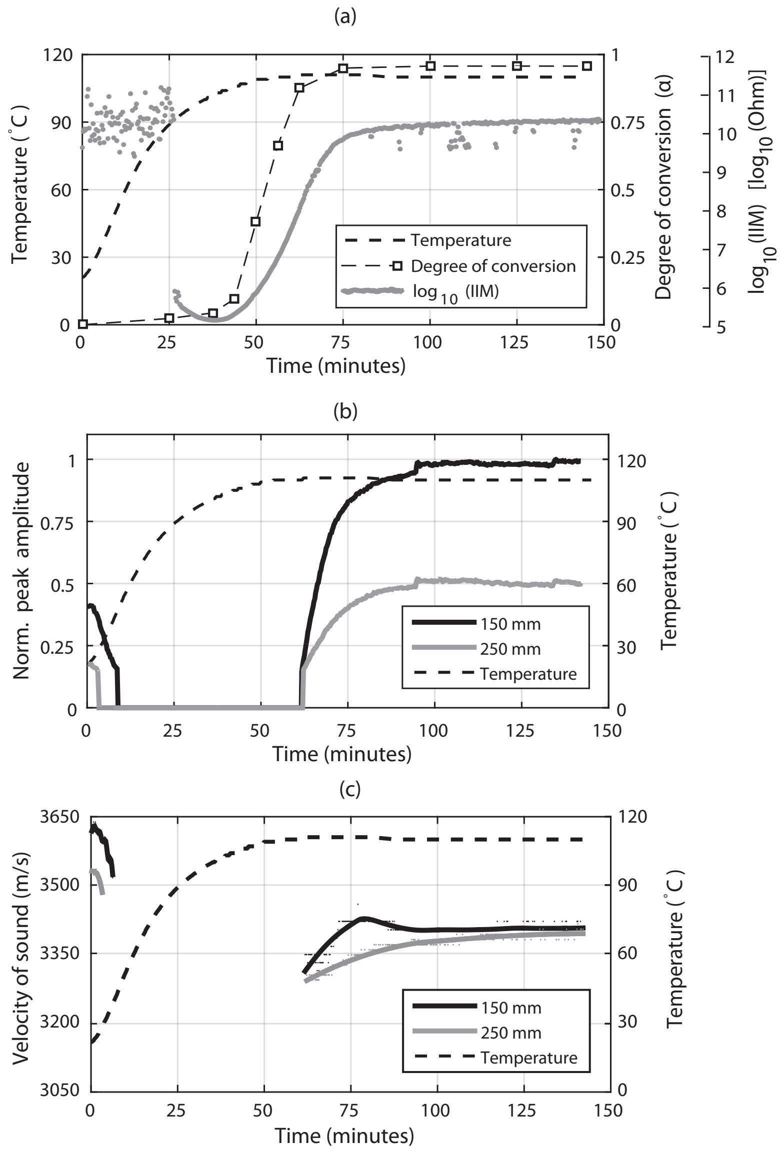

Figure 7. Data obtained from the cure of the glass fibre plate shown in Figure 2b. a) Degree of conversion measured by DSC, and the time evolution of the imaginary impedance maximum (IIM) recorded by dielectric analysis. b) Normalised amplitude of the edge reflections. c) Velocity of sound.

sensor identifying the edge reflections labelled in Figure 6. Upon application of an elevated temperature both the amplitude and velocity of the received edge reflections decreased, before both reflections were no longer identifiable (8 minutes into the curing process, Figure 7a and 7b). The increase in temperature decreased the viscosity of the resin, and increased the attenuation experienced by the propagating ultrasonic waves. 60 minutes into the cure cycle, the edge reflections became identifiable (labelled in Figure 6), there was a rapid increase in the amplitude, and steady rise in velocity between 60 and 75 minutes, indicating that the modulus of the curing resin had increased.

The final guided wave measurement to plateau was the velocity associated with the reflection received from the edge located 250 mm from the sensor, which reached a steady value at 130 minutes, indicating cure completion. There were two discrete jumps in the amplitude data captured by the ICTS, the jumps were present in the data for the reflections from both edges, with no change seen in the velocity data. It is not clear whether these changes are due to the cure reaction, or an external factor such as a change in vacuum pressure (which would vary the coil separation distance). Further testing will be conducted to investigate this effect.
The guided wave ICTS displayed a high sensitivity to the final stages of the curing process, with the measured ultrasonic data plateauing after the degree of conversion, and IIM measurements. However, the ultrasonic measurements made by the ICTS provided no information on the curing process between 8 and 60 minutes. In this region the large material attenuation experienced by the propagating waves prevented ultrasonic cure measurements being made.

4. Damage Detection

The primary aim of the ICTS is to detect structural damage events. In this section the guided wave sensor (previously used to monitor cure) embedded in the plate shown in Figure 2b, was used to detect BVID created by a low energy impact. In a previous study carried out by Zhong et al. [38], the influence of coil misalignment was studied, and techniques developed to help minimise its influence. In this work the effects of coil misalignment were not studied and the inductance wand was fixed to the panel shown in Figure 2b.

4.1. Experimental method

Prior to the plate being impacted, the inductance wand was fixed to the plate and damage free baseline measurements recorded. The plate was then subjected to a 10 Joule impact at a distance of 300 mm from the sensor (location shown in Figure 8). The 10 Joule impact resulted in a delaminated area about 20 mm in diameter, visible on the opposite face to that impacted. A second set of ultrasonic measurements were then recorded. To identify the damage, baseline subtraction techniques were applied. Baseline techniques use two sets of data; a damage free baseline and a current signal. The damage free baseline is subtracted from the current signal, leaving the residual signal. The residual signal is a combination of that due to noise and damage. Damage is identified when the residual signal exceeds a damage threshold. The advantage of using baseline techniques, is that the influence of a structures geometry is minimised. The signal processing techniques used by the ICTS to perform baseline subtraction are covered in more detail in the work of Zhong et al. [38].

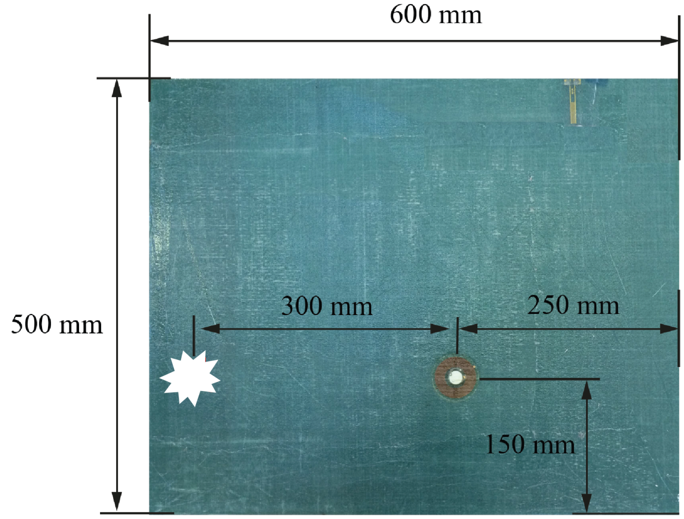

Figure 8. Dimensioned image of the glass fibre panel, showing the impact location at a distance of 300 mm from the sensor.

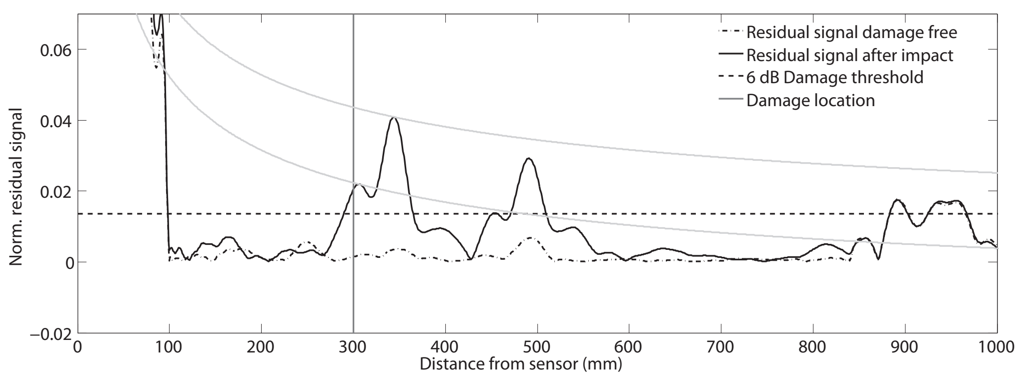

Figure 9. Residual signals before and after damage of the plate shown in Figure 8

4.2. Results

Figure 9 displays the residual signals before and after the plate shown in Figure 8 was subjected to a 10 Joule impact. Both the residual signals have been normalised with respect to amplitude of the first echo (from the edge 150 mm from the sensor, Figure 8). A damage threshold line is drawn onto Figure 9. The threshold was set as 6 dB greater than the peak noise in the undamaged baseline. From viewing Figure 9 it is clear that the damage is identifiable at the expected distance of 300 mm from the sensor. At the expected damage location (300 mm from the sensor, Figure 8) there is a 4.1 dB difference between the peak signal associated with the damage, and the 6 dB damage threshold. Behind the signal associated with the damage is a larger peak, which is 9.5 dB greater than the damage threshold. This shadowing effect is caused by the damage interacting the waveforms reflected from the edge located 350 mm from the sensor. Although this signal does not accurately locate damage in the plate, it can be used to identify the existence of damage. To provide predictions of the damage detection radius of the ICTS in a larger structure, the geometric attenuation of the generated So waves has been accounted for using an inverse square fit (plotted as grey lines, Figure 9). The results suggest a damage detection radius of 500 mm for the signal associated with the damage, and a radius of 3300 mm for the shadow signal.

5. Conclusion

This paper has demonstrated the capability of an ICTS to monitor the curing process of composite materials, and detect their subsequent structural condition once manufactured.

The sensors can be either embedded, or surface bonded to composite parts during layup and used to detect the progress of cure. A bulk wave system, which generated ultrasonic waves at a frequency 2 MHz that propagated in the through-thickness direction, was used to follow the progress of cure in a thick composite section (Figure 2a). A guided wave ICTS, which generated guided elastic waves at a frequency of 165 KHz that propogated in the plane of the fibres, monitored the curing progress of a large glass fibre panel (Figure 2b). The cure monitoring performance of the guided and bulk wave systems was similar; each system was highly sensitive to the final stages of the cure reaction. However, the majority of the cure reaction had to have taken place before ultrasonic measurements could be recorded by the embedded sensors. The high sensitivity to the final stages of cure suggests that embedded piezoelectric sensors could be a useful tool for detecting cure completion, when producing composite parts in an industrial manufacturing environment.

The guided wave sensor embedded in the large glass fibre plate was then used to detect BVID created by a 10 Joule impact at a distance of 300 mm (Figure 8). In this work the bulk wave ICTS was not used to detect damage, but in a previous study Zhong et al. [37] showed the bulk wave ICTS to be capable of detecting delaminations. The work in this paper has shown that an inductively coupled network of ultrasonic sensors can be used to monitor the state of health throughout the lifetime of a composite part; during manufacture as the part cures, and to detect damage during structural operation.

Acknowledgments

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